GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: September 7, 1977

Project Title: "An Experimental Fracture Mechanics Evaluation of Creep Induced Embrittlement."

Project No: E-16-624

Project Director: Dr. R. L. Carlson

Sponsor: National Science Foundation

Agreement Period: From 10/1/77 Until 3/31/80
(Includes the 6-month unfunded flexibility period.)

Type Agreement: Grant No. ENG77-04430

Amount: $45,000 (NSF share)
1,277 (E-16-314)
$46,277 TOTAL

Reports Required: Annual Technical Letter, Final Report.

Sponsor Contact Person (s):

Technical Matters

Dr. Clifford J. Astill, Director
Solid Mechanics Program
Engineering Mechanics Section
National Science Foundation
Washington, D. C. 20550

Contractual Matters
(thru OCA)

James L. Bostick, Grants Officer
National Science Foundation
Washington, D. C. 20550

Defense Priority Rating: N/A

Assigned to: Aerospace Engineering (School/Laboratory)

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GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: 10/31/80

Project Title: An Experimental Fracture Mechanics Evaluation of Creep Induced Embrittlement

Project No: E-16-624

Project Director: Dr. R. L. Carlson

Sponsor: National Sciences Foundation

Effective Termination Date: 3/31/80

Clearance of Accounting Charges: 3/31/80

Grant/Contract Closeout Actions Remaining:

- [ ] Final Invoice and Closing Documents
- [x] Final Fiscal Report
- [ ] Final Report of Inventions
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CA-4 (1/79)

ANNUAL REPORT

on

AN EXPERIMENTAL FRACTURE MECHANICS EVALUATION OF CREEP INDUCED EMBRITTLEMENT

NSF Grant ENG 77-04430

Period from Oct. 1, 1978 to Sept. 30, 1979

SCHOOL OF AEROSPACE ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY

PRINCIPAL INVESTIGATOR - R.L. CARLSON

SUMMARY

All of the experimental work planned for the research program has been completed and the data have been processed. The objective of the investigation was to determine the feasibility of using fracture toughness as a measure of the embrittlement induced by creep. This objective has been achieved and it has been demonstrated that a quantitative measure of the resistance to crack extension can be obtained for an alloy subjected to conditions producing creep embrittlement.

Although the theory of fracture mechanics can be used to determine the critical crack length for a given structural configuration and loading, the embrittlement process produces a time dependent critical crack length. For the Cr-Mo-V steel studied, the critical crack length decreases with increasing time under creep because the fracture toughness decreases with time.

The time dependency of fracture toughness can also be expected to complicate the analysis of stable creep crack growth. For although some recent success has been achieved in relating the conditions at a crack tip to the rate of stable creep crack growth, the time to unstable crack extension can only be computed when the critical crack length is known. Since this quantity depends on the time dependent fracture toughness, this suggests that a continuous monitoring of toughness will be required.

RESEARCH ACTIVITY AND RESULTS

Activity during the second and final year of the program was concerned with completing the experimental work, processing test data and analyzing the results. Standard short-time tensile tests and creep rupture tests were conducted to provide basic data on the Cr-Mo-V steel 17-22A (5) used. The heat treatment used was:

1. Austinitize for ½ hour at 2000°F and then air cool.
2. Temper for 6 hours at 1200°F and air cool.

A special experimental procedure was designed to evaluate the effect of creep induced embrittlement on fracture toughness. Tensile creep tests were conducted at a stress of 33,400 psi for the four times of zero, 6, 42, 100 hours. A total of four specimens were made available for each creep interruption time and these specimens were machined into notched bend specimens. A fatigue crack was then introduced under three point loading into each bend specimen. The crack lengths were monitored to ensure that the same length was developed in each specimen. The cracked bend specimens provided the means for determining fracture toughness for different amounts of exposure to creep. All of the creep tests were conducted at a temperature of 1100°F and since this would correspond to a service temperature, the toughness determinations were also made at 1100°F. A special three point bend fixture with an extensomter for measuring the beam deflection was made for these experiments.

It was anticipated that the test material would not be brittle enough for all conditions to measure fracture toughness in terms of K_{IC}. To account for inelastic effects on crack extension, the bend tests were designed to provide a measurement of J_{IC}.

A method for determining J_{IC} has been suggested by Rice etal(1) and developed for three point bending by Landes and Begley (2). This method was adopted for use in our program and values of J_{IC} were obtained for each of the creep test times. The results are presented in the table below.

Table 1. Effect of Creep on J_{IC} Values

Creep Time (hours)	J_{IC} (inch lb/inch)
0	410
6	310
42	78
100	76

The embrittlement indicated by the results in table 1 is substantial and shows that for this material, the heat treatment and test conditions have produced a time dependent fracture toughness. The reduction in the capacity to absorb energy in the crack extension process is also illustrated by a comparison of the bending load - deflection curves for zero and 100 hours of creep in the following figure.

Embrittlement effects have been described for this alloy by Jones et al (3). Based on comparisons of notched and unnotched stress rupture tests, they found that notch sensitivity occurs in about ten hours for a normalization temperature of 2000^{O}F and a test temperature of 1000^{O}F. The rapid embrittlement observed here for a test temperature of 1100^{O}F is consistent with their results.

Jones et al (3) attribute embrittlement for this alloy to carbide precipitation. From one of our creep rupture specimens which ruptured after 139.2 hours at 42,600 psi, it might be inferred that embrittlement led to the intergrannular cracking which was found upon sectioning the specimen. This type of cracking behavior has led many investigators to conduct research on the mechanisms leading to the formation of cracks (4).

To investigate the possibility that intergrannular cracks may have influenced the fracture toughness determinations, one of the tested bend specimens was sectioned and metallographically examined. A specimen, which had been subject to precreep for 100 hours, exhibited no intergrannular cracking. Since the level of fracture toughness was very low for this test condition, the embrittlement clearly occurred before the generation of cracks. This suggests that the cracking which occurred in the stress rupture test developed as a part of the final failure process near the end of the test.

The results suggest that failure due to fracture because of embrittlement could occur when the time-dependent fracture toughness is reduced to a value which makes an existing crack critical. In some applications then, the danger of failure through fracture may not be associated with the nucleation and growth of cracks, but rather to creep induced metallurgical reactions which reduce fracture toughness.

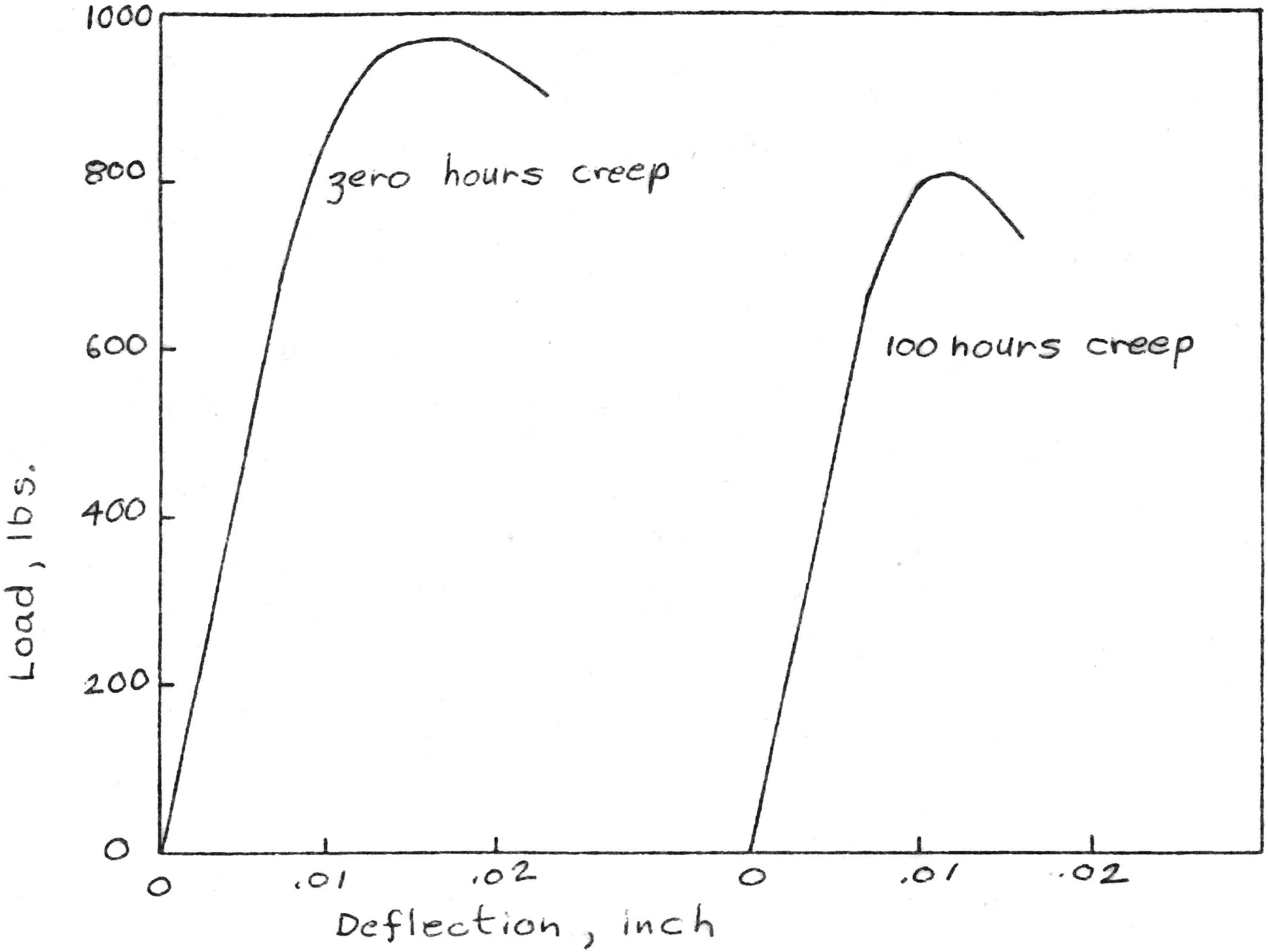

Figure. Comparison of load-deflection curves.

The preceding discussion has emphasized the role of embrittlement processes in the fracture process. To provide more insight into these issues, electron microscope examinations of fracture surfaces are being conducted. These results will be presented in the final report on this program.

The discussion to this point has been concerned primarily with the conditions for unstable crack growth. A considerable effort has been directed by researchers to the study of stable crack growth due to creep, and this work should be discussed in relation to the results presented here.

The objective of the creep crack growth studies has been to develop relations which correlate the rate of crack growth with the stress and strain or strain rate at the crack tip. Initial efforts made use of the stress intensity factor and good correlations were found for high strength, low ductility materials. This would appear to reflect the fact that this is a reasonable extension of linear elastic fracture mechanics. A more general development has been presented by Landes and Begley (5) and by Nikbin et al (6), and this is intended for materials which are not necessarily brittle. In each of these methods a creep crack growth rate relation is obtained and the crack growth history can be obtained by integration. To obtain the time at which a crack becomes unstable, however, the critical crack length must be determined. The critical crack length depends on the fracture toughness and, in terms of the present work it can be time dependent. It would appear, then, that if the creep crack growth relations are to be useful, a satisfactory procedure must be developed for computing the critical crack length.

REFERENCES

1. Rice, J.R., Paris, P.C. and Merkle, J.G., "Some Further Results on J Integral Analysis and Estimates," ASTM STP 536, American Society for Testing and Materials," Philadelphia, 1973, pp. 231-245.

2. Landes, J.D. and Begley, J.A., "Test Results from J. Integral Studies," ASTM STP 560, American Society for Testing and Materials, Philadelphia, 1974, pp. 170-186.

3. Jones, M.H., Newman, D.P., Sachs, G. and Brown Jr., W.F., "Effects of Variation in Normalizing and Tempering Procedure on Stess Rupture Strength, Creep Embrittlement and Notch Sensitivity for a Cr-Mo-V and a 17 Cr-4Ni-Cu Steel," transactions of the ASM, Vol. 47, 1955, pp. 926-954.

4. Garofalo, F., <u>Fundamentals of Creep and Creep Rupture in Metals</u>, the Macmillan Company, New York, 1965, pp. 213-241.

5. Landes, J.D. and Begley, J.A., "A Fracture Mechanics Approach to Creep Crack Growth," ASTM STP 590, American Society for Testing and Materials, Philadelphia, 1976, pp. 128-148.

6. Nikbin, K.M., Webster, G.A. and Turner, C.E., "Relevance of Nonlinear Fracture Mechanics to Creep Cracking," ASTM STP 601, American Society for Testing and Materials, Philadelphia, 1976, pp. 47-62.

MOST SIGNIFICANT ACCOMPLISHMENT

The most significant accomplishment of the research program was the demonstration that fracture mechanics techniques can be used to provide a quantative measure of creep induced embrittlement. It was shown that fracture toughness in the Cr-Mo steel investigated decreased substantially before the development of intergrannular cracking. This indicates that failure due to fracture could occur when the time-dependent fracture toughness is reduced through creep induced embrittlement to a value which makes an existing crack critical. In some applications, therefore, failure by fracture may not be the result of nucleation and growth of cracks, but rather to creep induced metallurgical reactions which reduce fracture toughness.

The high temperature alloys commonly used are complex and the occurrence of metallurigical reactions in service is highly probable. Also, since such reactions are stress as well as time and temperature dependent, the effects on fracture toughness can be expected to require extensive investigation. If knowledge of these effects is not made available, however, it will not be possible to predict resistance to unstable crack extension.

The time dependent nature of fracture toughness in creep environments has implications which can also have an affect on another area of research in high temperature technology. Considerable recent research has been directed toward the development of methods for predicting stable creep crack growth.

Recently Landes and Begley (5) and Nikbin et al (6), working on the problem of creep crack growth, have proposed the use of a path independent integral which is analogous to the J-integral introduced by Rice. In this work a steady state creep law is used in which the creep strain rate is nonlinearly proportional to stress. Also, displacement rates replace the displacements of the J integral. Landes and Begley (5) define the new integral by the symbol C^* and Nikbin et al (6) use the symbol $\dot{J}$. Since these quantities are equivalent, $C^* = \dot{J}$. Whereas J may be identified as an energy release rate associated with crack extension, C^* is interpreted as a power release rate for creep crack growth.

Landes and Begley (5) and Nikbin et al (6) have presented experimental results from which they infer that C* may characterize the stress and strain rate state at the creep crack tip. Also, Nikbin et al (6) observed that the available data indicate that the creep crack growth rate is linearly proportional to C*.

In each of these methods a creep crack growth rate relation is obtained so the crack growth history should be obtainable by integration. To obtain the time at which a crack becomes unstable, however, the critical crack length must be known. The critical crack length depends on the fracture toughness and, in terms of the present work, it can be time dependent. It would appear, then, that if the creep crack growth relations are to be useful, a satisfactory procedure must be developed for computing the critical crack length. The results of the research program conducted have, therefore, indicated that ultimately the affect of a time dependent fracture toughness must be considered if the problem of a transition from stable creep crack growth to unstable crack extension is to be solved.

PERSONNEL

The principal investigator was Professor Carlson. Mr. H. Lo, a graduate student in the School of Aerospace Engineering participated in the research program and used some of the results in his thesis for the Ph.D. degree which he earned in June 1978. Mr. J. Kovats, a machinist, assisted by making test specimens and fixtures for the experimental work.

PUBLICATIONS

A paper describing the results of the investigation is being prepared and it will be submitted for publication to the International Journal of Fracture Mechanics.

E-16-624

GEORGIA INSTITUTE OF TECHNOLOGY

ATLANTA, GEORGIA 30332

SCHOOL OF
AEROSPACE ENGINEERING

404-894-3000

DANIEL GUGGENHEIM SCHOOL
OF AERONAUTICS

March 12, 1980

National Science Foundation
Washington, D.C. 20550

Attention: Dr. Clifford J. Astill, Director
Solid Mechanics Program
Engineering Mechanics Section
Directorate for Engineering and Applied Science

Dear Dr. Astill:

I am enclosing two copies of the Final Technical Report on our program under NSF Grant ENG 77-04430. Two copies of the Final Project Report Form have also been completed and are included. The Final Fiscal Report (NSF Form 98) will be submitted separately.

The objectives of our program have been achieved and we would like to take this opportunity to express our thanks for your support.

Sincerely,

R.L. Carlson
Professor
School of Aerospace Engineering

RLC/bc
Enclosure

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT
NSF FORM 98A

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

PART I–PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. NSF Program	3. NSF Award Number
Georgia Institute of Technology Atlanta, Georgia 30332	Solid Mechanics	ENG 77-04430
	4. Award Period From 10/1/77 To 3/31/80	5. Cumulative Award Amount $45,000

6. Project Title

An Experimental Fracture Mechanics Evaluation of Creep Induced Embrittlement

PART II–SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

Metals used in structural systems which are exposed to both loads and high temperature environments often become brittle. This is undesirable because the structural element which is made of the metal then becomes more susceptible to catastrophic failure. The objective of the investigation was to develop a method for measuring the loss in strength due to embrittlement of metals exposed to high temperature environments. A method based on the resistance of the metal to the extension of an existing crack was examined. It was shown that exposure to load and temperature can progressively decrease the resistance to crack extension in a metal subject to embrittlement. An examination of the fracture surfaces revealed that crack extension occurred along grain boundaries and this is evidence of grain boundary embrittlement. It is concluded that the time dependency of the resistance to crack extension will complicate the analysis of a crack growing under stress at high temperatures. This follows because although methods for determining the length of growing cracks are available, the time at which unstable growth begins cannot be determined unless the critical crack length can be computed.

PART III–TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRA[M] Check (√)	Approx. Date
a. Abstracts of Theses		X			
b. Publication Citations			X		
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e. Technical Description of Project and Results		X			
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2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date
Robert L. Carlson		3-14-8[0]

Ph.D. THESIS ABSTRACT - H.LO.

A fracture mechanics evaluation of creep induced embrittlement of the steel alloy 17-22A(S) at an elevated temperature of 1100°F has been made. It was concluded that fracture mechanics techniques can be used to measure the deterioration or embrittlement of the tested material in terms of residual fracture toughness under creep condition at high temperature.

The results obtained from this research indicate that the embrittlement effects previously detected by use of the notched and unnotched creep tests as well as some other methods can be detected and determined quantitatively by use of fracture mechanics techniques. The test results obtained by the use of fracture mechanics techniques, however, can be more readily used in design problems because they can be incorporated in stress and strain analyses.

It was found that fracture toughness for the material used was not a constant but rather to be time dependent under the testing conditions. Furthermore, since embrittlement reactions can be expected to be temperature and creep stress level dependent, the potential problems involved in design considerations may make an analysis quite difficult.

FINAL TECHNICAL REPORT

on

AN EXPERIMENTAL FRACTURE MECHANICS EVALUATION OF CREEP INDUCED EMBRITTLEMENT

NSF Grant ENG 77-04430

Period from Oct. 1, 1977 to Jan. 31, 1980

SCHOOL OF AEROSPACE ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY

PRINCIPAL INVESTIGATOR - R.L. CARLSON

SUMMARY

The objective of the investigation was to determine the feasibility of using fracture toughness as a measure of embrittlement induced by creep. This objective has been achieved and it has been demonstrated that a quantitative measure of the resistance to crack extension can be obtained for an alloy subjected to conditions producing creep embrittlement.

Although the theory of fracture mechanics can be used to determine the critical crack length for a given structural configuration and loading, the embrittlement process produces a time dependent critical crack length. For the Cr-Mo steel studied, the critical crack length decreases with increasing time under creep because the fracture toughness decreases with time.

A fractographic examination indicates that intergranular fracture occurs both in stress rupture tests and in fracture toughness tests in which crack extension develops from transgranular fatigue cracks. For the alloy studied this provides evidence of grain boundary embrittlement.

The time dependency of fracture toughness observed can be expected to complicate the analysis of stable creep crack growth. For although some recent success has been achieved in relating the conditions at a crack tip to the rate of stable creep crack growth, the time to unstable crack extension can only be computed when the critical crack length is known. Since this quantity depends on the time dependent fracture toughness, a continuous monitoring of toughness may be required.

RESEARCH ACTIVITY AND RESULTS

All of the experiments were conducted on the Cr-Mo steel 17-22-AS which was heat treated by austinitizing for ½ hour at 2000°F, air cooling and then tempering for 6 hours at 1200°F followed by an air cool. Standard short-time tensile tests and creep rupture tests were conducted to obtain basic data.

A special experimental procedure was developed to evaluate the effect of creep induced embrittlement on fracture toughness. Tensile creep tests were conducted at 1100°F at a stress of 33,400 psi for the four times of zero, 6, 42, 100 hours. A total of four specimens were made available for each creep interruption time and these specimens were machined into notched bend specimens. A fatigue crack was then introduced under three point loading into each bend specimen. The cracked bend specimens provided the means for determining fracture toughness at 1100^{o}F for different amounts of exposure to creep.

To account for inelastic effects on crack extension, the bend tests were designed to provide a measurement of J_{IC}. A method for determining J_{IC} has been suggested by Rice et al (1) and developed for three point bending by Landes and Begley (2). This method was adopted for use in our program. The results are presented in the table below.

Table Effect of Pre-Creep on J_{IC} Values

Creep Time (hours)	J_{IC} (inch lb/inch)
0	410
6	310
42	78
100	76

The embrittlement indicated by the results in the Table is substantial and shows that for this material, the heat treatment and test conditions have produced a time dependent fracture toughness. The results obtained are compatible with embrittlement effects observed for this alloy by Jones et al (3). They based comparisons on the use of notched and unnotched stress rupture tests.

Jones et al (3) attribute embrittlement for this alloy to carbide precipitation. From one of our creep rupture specimens which ruptured after 139.2 hours at 42,600 psi, it might be inferred that embrittlement led to the intergranular cracking which was found upon sectioning the specimen. This type of cracking behavior has led many investigators to conduct research on the mechanisms leading to the formation of cracks (4).

To investigate the possibility that intergranular cracks may have influenced the fracture toughness determinations, one of the tested bend specimens was sectioned and metallographically examined. The specimen, which had been subject to precreep for 100 hours, exhibited no intergranular cracking. This indicates that the decrease in fracture toughness occurred before the onset of intergranular cracking.

The results suggest that failure due to fracture because of embrittlement could occur when the time-dependent fracture toughness is reduced to a value which makes an existing crack critical. In some applications then, the danger of failure through fracture may not be associated with the nucleation and growth of cracks, but rather to creep induced metallurgical reactions which reduce fracture toughness.

Although the fracture toughness results contribute insight into the resistance to crack extension, they do not provide information on the details of the fracture process. To provide this type of perspective a scanning electron microscope (5,6) was used to examine some of the fracture surfaces.

The fracture surface of a stress rupture specimen which fractured in 67.4 hours is shown in Figures 1 and 2. A visual examination of the surface indicates that fracture was intergranular and this is clearly confirmed at both levels of magnification.

The fracture surface of a specimen exposed to 100 hours creep is shown in Figures 3 and 4. The fatigue crack surface is shown on the bottom of Figure 3 and the surface resulting from crack extension or popin in the fracture toughness test is shown on the top. The transition boundary is quite clear and the modes of crack extension are distinctly different. The fatigue fracture surface is transgranular and the popin fracture surface is intergranular.

An inspection of Figures 2 and 4 reveals the presence of dimples on the fracture surfaces of both test specimens. The dimples, which are indicative of highly localized plastic deformation (5), appear to be more shallow and less extensive on the stress rupture surface than on the popin surface. This suggests that the formation of the popin surface involves a greater absorption of energy due to plasticity.

The results of the fractographic examination indicate that for the given test conditions the mode of fracture is the same when extension occurs by the growth of intergranular microcracks in stress rupture and when extension develops from a transgranular fatigue crack. This occurs in spite of the fact that the rates of crack growth are substantially different, and it provides evidence of grain boundary embrittlement.

A considerable effort has been directed recently by researchers to the study of stable crack growth due to creep. The objective of stable creep crack growth studies has been to develop relations which correlate the rate of crack growth with the stress and strain or strain rate at the crack tip (7, 8). Initial efforts made use of the stress intensity factor and good correlations were found for high strength, low ductility materials. This would appear to reflect the fact that this is a reasonable extension of linear elastic fracture mechanics. A more general development has been presented by Landes and Begley (7) and by Nikbin et al (8), and this is intended for materials which are not necessarily brittle. In each of these methods a creep crack growth rate relation is obtained and the crack growth history can be obtained by integration. To obtain the time at which a crack becomes unstable, however, the critical crack length must be determined. The critical crack length depends on the fracture toughness and, in terms of the present work it can be time dependent. It would appear, then, that if the creep crack growth relations are to be useful, a satisfactory procedure must be developed for computing the critical crack length.

REFERENCES

1. Rice, J.R., Paris, P.C. and Merkle, J.G., "Some Further Results on J Integral Analysis and Estimates," ASTM STP 536, American Society for Testing and Materials," Philadelphia, 1973, pp. 231-245.

2. Landes, J.D. and Begley, J.A., "Test Results from J. Integral Studies," ASTM STP 560, American Society for Testing and Materials, Philadelphia, 1974, pp. 170-186.

3. Jones, M.H., Newman, D.P., Sachs, G. and Brown Jr., W.F., "Effects of Variation in Normalizing and Tempering Procedure on Stress Rupture Strength, Creep Embrittlement and Notch Sensitivity for a Cr-Mo-V and a 17 Cr-4Ni-Cu Steel," transactions of the ASM, Vol. 47, 1955, pp. 926-954.

4. Garofalo, F., Fundamentals of Creep and Creep Rupture in Metals, the Macmillan Company, New York, 1965, pp. 213-241.

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6. Hubbard, J.L., "A Comparison Atlas of Electron and Scanning Electron Fractography," M.S. Thesis, School of Chemical Engineering, Georgia Institute of Technology, June 1971.

7. Landes, J.D. and Begley, J.A., "A Fracture Mechanics Approach to Creep Crack Growth," ASTM STP 590, American Society for Testing and Materials, Philadelphia, 1976, pp. 128-148.

8. Nikbin, K.M., Webster, G.A. and Turner, C.E., "Relevance and Nonlinear Fracture Mechanics to Creep Cracking," ASTM STP 601, American Society for Testing and Materials, Philadelphia, 1976, pp. 47-62.

MOST SIGNIFICANT ACCOMPLISHMENTS

The most significant accomplishments of the research program are listed below.

1. It was demonstrated that fracture mechanics techniques can be used to provide a quantative measure of creep induced embrittlement. It was shown that fracture toughness in a Cr-Mo steel decreased substantially before the development of intergranular cracking. This indicates that failure due to fracture could occur when the time-dependent fracture toughness is reduced through creep induced embrittlement to a value which makes an existing crack critical. In some applications, therefore, failure by fracture may not be the result of nucleation and growth of cracks, but rather to creep induced metallurgical reactions which reduce fracture toughness.

2. The results of a fractographic examination indicated that intergranular fracture can occur both when extension occurs by the growth of intergranular microcracks in stress rupture and when extension develops from a transgranular fatigue crack in the fracture toughness test. This occurs in spite of the fact that the rates of crack growth are substantially different for these two conditions and it provides evidence of metallurgical reactions.

3. The role of metallurgical reactions is important. Jones et al (3) have indicated that for the alloy studied the carbide distribution within the grains and at the grain boundaries controls the embrittlement response. Since the initial distribution is established by the normalizing and tempering treatments, a variety of responses can be developed. It is

conceivable, therefore, that heat treatments different from that used in the current investigation could result in different modes of crack extension. This potential variation in response may be typical because high temperature alloys commonly used are complex and the occurrence of metallurgical reactions in service is highly probable. Also, since such reactions are stress as well as time and temperature dependent, the effects on fracture toughness can be expected to be quite complicated.

4. The time dependent nature of fracture toughness in creep environments has implications which can also have an affect on another area of research in high temperature technology. Considerable recent research has been directed toward the development of methods for predicting stable creep crack growth. Recently Landes and Begley (7) and Nikbin et al (8), working on the problem of creep crack growth, have proposed the use of a path independent integral which is analogous to the J-integral introduced by Rice. In this work a steady state creep law is used in which the creep strain rate is nonlinearly proportional to stress. Also, displacement rates replace the displacements of the J integral. Landes and Begley (7) define the new integral by the symbol C^* and Nikbin et al (8) use the symbol $\dot{J}$. Since these quantities are equivalent, $C^* = \dot{J}$. Whereas J may be identified as an energy release rate associated with crack extension, C^* is interpreted as a power release rate for creep crack growth. Landes and Begley (7) and Nikbin et al (8) have presented experimental results from which they infer that C^* may characterize the stress and strain rate state at the creep crack tip. Also, Nikbin et al (8) observed that the available data indicate that the creep crack growth rate is linearly proportional to C^*. In each of these methods a creep crack growth rate relation is obtained so the crack growth history should be obtainable by integration. To obtain the time at which a crack becomes unstable, however, the critical crack length must be known. The critical crack length depends on the fracture toughness and, in terms of the present work, it can be time dependent. It would appear, then, that if the creep crack growth relations are to be useful, a satisfactory procedure must be developed for computing the critical crack length. The results of the research program conducted have, therefore, indicated that ultimately the affect of a time dependent fracture toughness must be considered if the problem of a transition from stable creep crack growth to unstable crack extension is to be solved.

PERSONNEL

The principal investigator was Professor Carlson. Mr. H. Lo, a graduate student in the School of Aerospace Engineering participated in the research program and used some of the results in his thesis for the Ph.D. degree which he earned in June 1979. Mr. J. Kovats, a machinist, assisted by making test specimens and fixtures for the experimental work.

PUBLICATIONS

A paper describing the results of our investigation has been prepared and submitted for publication to the International Journal of Fracture Mechanics.

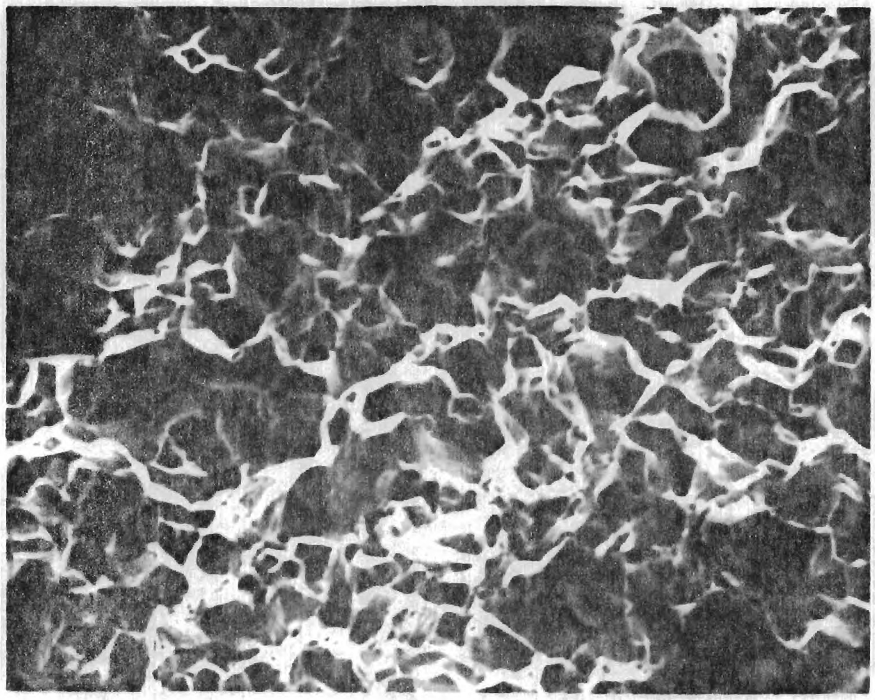

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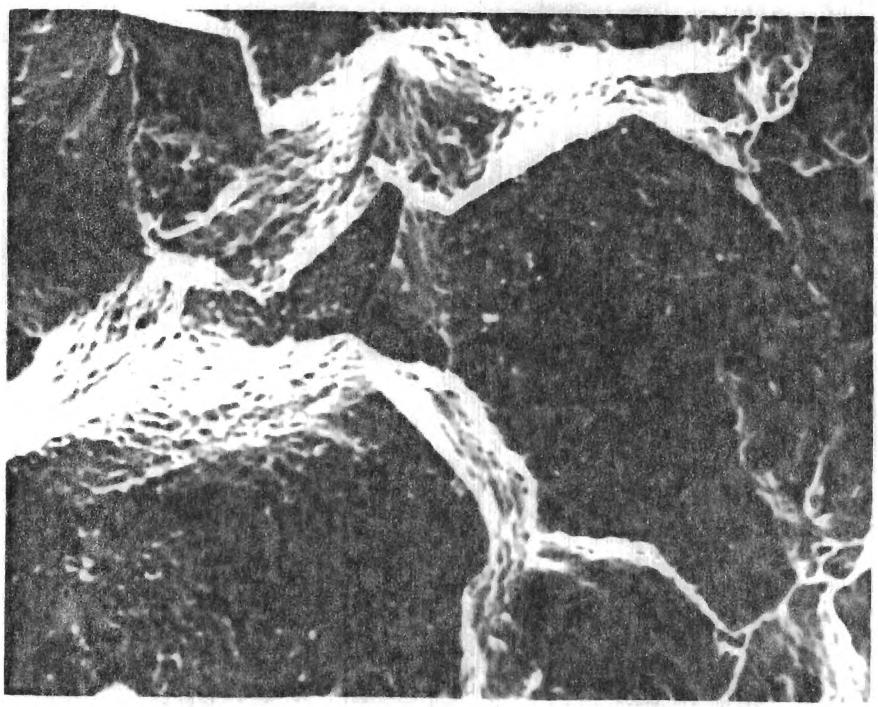
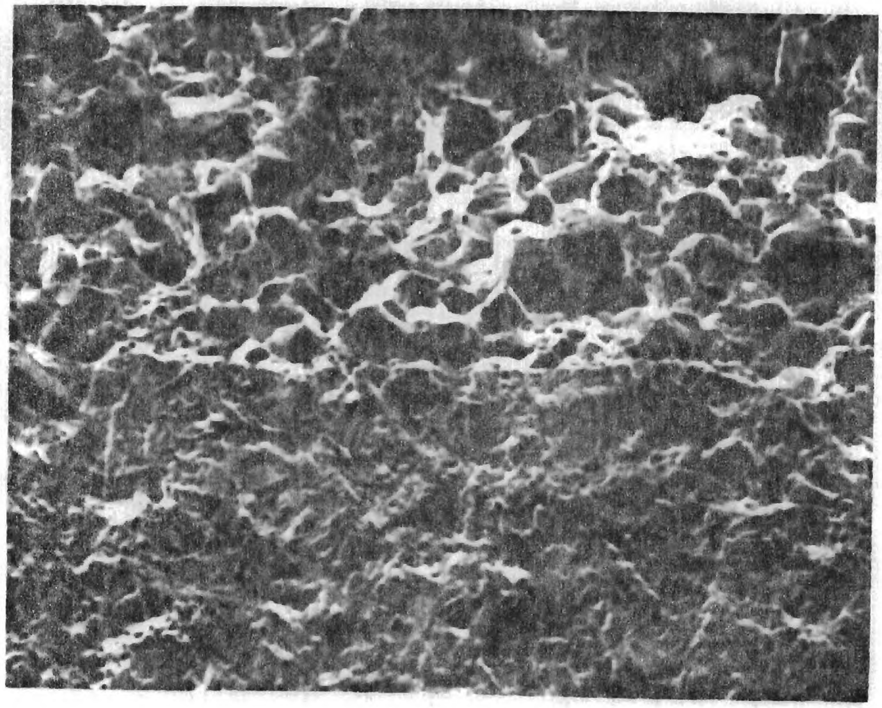
Figure 1. Stress rupture surface.



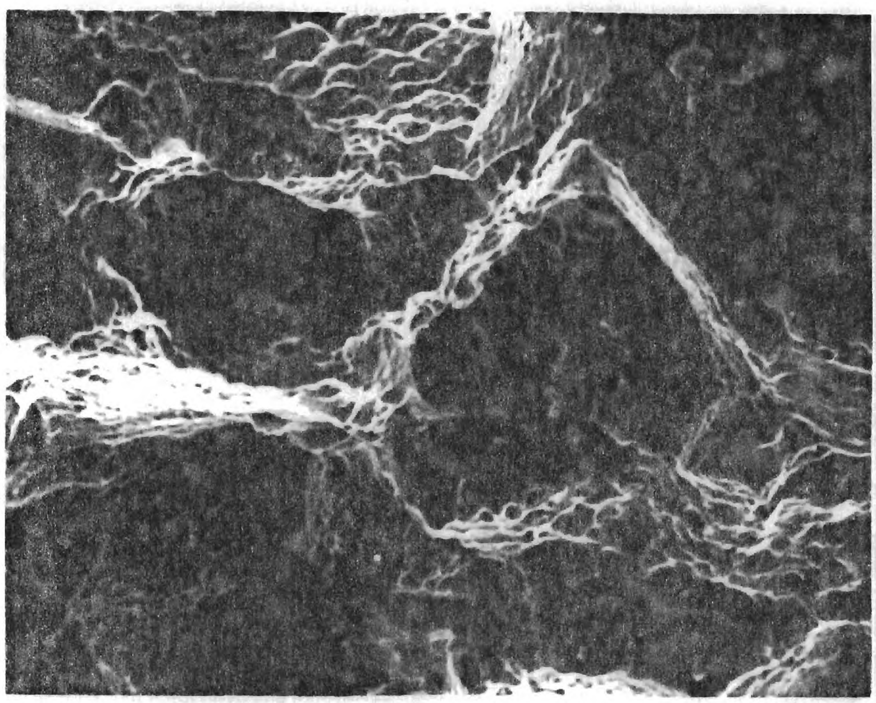
750X

Figure 2. Stress rupture surface.



100X

Figure 3. Fracture surface of precrept specimen.



750X

Figure 4. Fracture surface of precrept specimen.